REALISATION OF
A SOLID-STATE DISTANCE RELAY
FOR PROTECTION OF EHV TRANSMISSION LINE

DISSERTATION SUBMITTED
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BY

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CERTIFICATE

Certified that the dissertation entitled "Realization of a solid-state distance relay for protection of EHV transmission line", which is being submitted by Mr. Md. Syed Jamil Asghar in partial fulfilment of the requirements for the award of the degree of Master of Science in Electrical Engineering (Systems Engineering) of the Aligarh Muslim University, Aligarh, is a record of the candidate's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

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SYNOPSIS

This dissertation work deals with the design, fabrication and testing of a quadrilateral characteristics for a distance relay. Integrated circuits with descrete passive components are used for circuit realization. The testing of the relay is performed in steady-state conditions, with the help of an artificial transmission line. Experimental results are in good agreement with theory.

C O N T E N T S

CHAPTER - I

I N T R O D U C T I O N

INTRODUCTION

Electricity plays a vital role in the development of a country from agriculture to industry. Bulk of electric power is generated and transmitted to load centres through transmission lines to transmit huge amount of electric power economically, from an area with abundant hydro-power or thermal power near the coal mine sites, to an area of heavy electrical load, long distance extra high voltage (EHV) transmission lines are used. On most of the transmission systems a line is expected to be stable during system switching and faults if line length (L, in miles) is less than its KV rating[1]. Further, for economical operation the suggested line length, L is less than one-fourth of its KV rating[1]. In cases where the lengths of transmission lines are uneconomical for a given transmission voltage, compensation techniques are employed to reduce effective line lengths. Various compensation techniques are discussed in Chapter II. Chapter III covers various conventional protection schemes for EHV lines and effects of power swings upon protective relays. It is concluded that the quadrilateral characteristics is most suited for EHV lines from the power swings viewpoint. In Chapter IV, a combination of two quadrilateral characteristics is proposed for a series compensated line. The schematic block diagram is also suggested to obtain such a characteristics using phase sequence detectors. Realization aspects including design of various blocks of the proposed scheme are covered in Chapter V. The proposed quadrilateral characteristics is realized using analog and digital integrated circuits (ICs).

Several authors have worked on solid-state distance relays (mho-type) based on phase comparison techniques, using mostly transistorized circuits with or without full-wave rectifier bridges[1,2,3,4], or coincidence circuit with or without level detectors[6,7]. Some authors made use of zero crossing instants of the input signal to realize these characteristics using complicated transistorized circuits[8,9]. Phase sequence detection technique which is most attractive among all the above mentioned techniques is also found in literature[1,10,11]. Basu & Khan suggested a large transistorized network, to realize quadrilateral characteristics[10], using phase sequence detectors[12], suitable for EHV-lines. The transistorized network having large number of components suffers from difficulties of realization, lack of compactness, more power drainage etc. The reliability of circuit which is very important in relays also depends on proper functioning of a large number of components.

In this dissertation work a quadrilateral characteristic which is suitable for series compensated EHV line, is realized using phase sequence detection technique. In realization, ICs are used to replace large discrete components which makes the circuit compact and reliable.

The relay is tested using an artificial transmission line. The testing procedure and experimental results are included in Chapter VI. The photographs of waveshapes at important points observed during testing are given in Appendix. And finally in Chapter VII, some modifications in the present circuit are suggested to make it suitable for some other functions.

CHAPTER - II

COMPENSATION IN EHV TRANSMISSION LINES

COMPENSATION IN EHV TRANSMISSION LINES

Economy and flexibility of operation considerations encouraged to adopt higher and higher voltages in transmission line to transmit bulk of power over very long distances, such as from an area with abundant hydro-power to an area of heavy electrical load. Similarly remote locations of super thermal power stations (near the coal mines etc.) and nuclear power stations (near the sea or other big water sources) from the load centres forced to adopt long distance high voltage transmission lines. The choice of voltage for EHV links (above 230 KV)[13] depends upon the geographical size of the system (i.e. the distances involved) and the power to be transmitted (proportional to square of voltage) and also whether series capacitors, shunt reactors and fast automatic regulators are used. EHV lines up to 765-KV stretched over thousands of kilometers are in operation in different developed countries like U.S.A., Canada, U.S.S.R. etc.[14,15,16]

In long lines, the large line impedance restricts the amount of power transmitted through it and also leads to poor voltage regulation. The power through the line can be increased by increasing the phase angle between the sending and receiving end voltages. This however, reduces the stability margin and makes the system more liable to become unstable. The situation can be improved by reducing the line impedance. The line impedance comprises of series R-L and shunt G-C elements. The shunt conductance (G) being small can be neglected leaving with series R-L and shunt C elements as shown by an equivalent π-network in Fig. 2-1. The reduction in the resistance R of the line below a certain limit is not possible since it requires an increase in the area of cross-section of the conductor, which is not advisable due to economic reasons. Moreover its contribution to total line impedance is insignificant (about 5 to 10% in EHV lines)[1,17]. Hence efforts are being made to achieve reduction of other elements. The reduction in the values of L and C elements are achieved by compensation techniques, which include the use of bundled conductors, series capacitors and shunt reactors. The detailed discriptions of compensation techniques are given below.

(i) Bundled conductors: - A group of conductors of each phase, separated by conducting spacers and supported by same insulators are called bundled conductors.

Two and four bundled conductors, are in common practice and eighteen bundled conductors are under test for EHV/UHV lines[18]. The inductance perphase reduces drastically by bundling the conductors, resulting into lower reactance. Hence improving stability limits as well as regulation. Bundled conductor lines have a higher capacitance to ground therefore improving the power factor. The low inductive reactance decreases the surge impedance, thus increasing the surge impedance loading (SIL) and hense the power transmitting capacity of the line. Corona and resistive losses in the lines reduce and critical corona

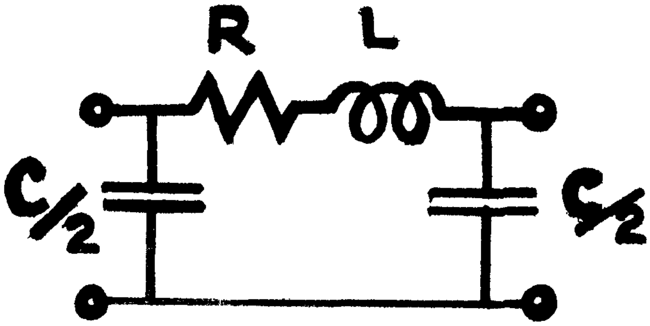


FIG.2-1 REPRESENTATION OF TRANSMISSION LINE IMPEDANCE.

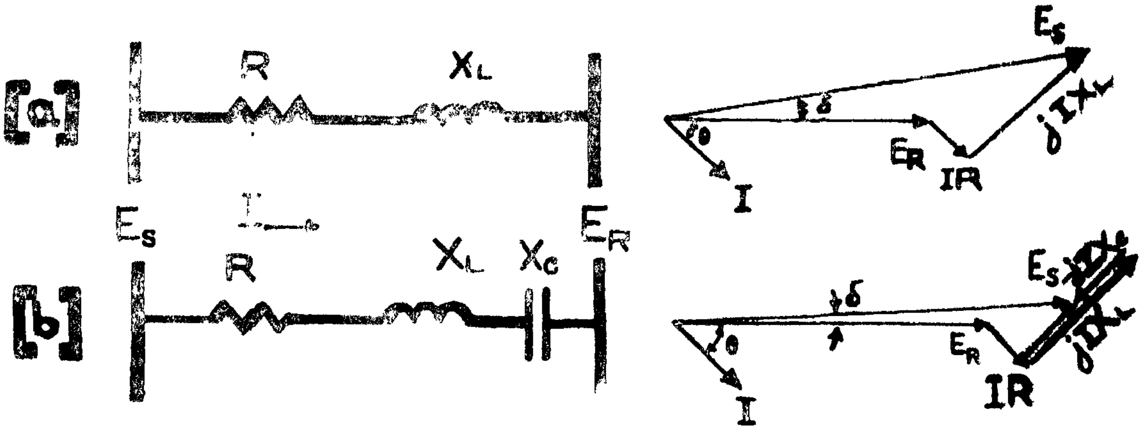


FIG. 2-2, VOLTAGE VECTOR DIAGRAM OF TRANSMISSION LINE (a) WITH AND (b) WITHOUT SERIES CAPICITORS.

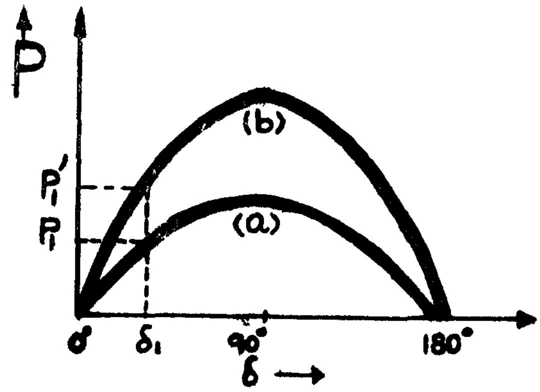


FIG. 2-3

RELATIVE POWER TRANSFER ABILITY (a) WITH AND (b) WITHOUT SERIES CAPACITORS.

(ii) Series compensation:- It is done by placing capacitor banks in series at the ends or in the middle of the transmission line. A series capacitor introduces a negative or leading reactance in an a.c. circuit. Thus it compensates for the drop, or part of the drop through highly inductive reactance of an EHV transmission line at rated frequency.

The stability requirements limit the permissible power on EHV lines, which decreases with increasing line length. Since the series capacitors (SC) reduces voltage drop in transmission line by reducing the highly reactive drop from IX_L to $I(X_L - X_C)$, where I, X_L and X_C are line current, line reactance and series capacitor reactance respectively. Hence receiving end voltage increases, load angle decreases and stability improves (vide Fig. 2-2). As power transfer is inversely proportional to the reactance of the line (neglecting the resistances) and is given by

$$P = \left(E_S E_R \operatorname{Sin} \delta\right) / X_L$$

where E_S and E_R are sending and receiving end voltages magnitudes, respectively. With a SC the expression becomes

$$P = \left(E_S\ E_R \operatorname{Sin} \delta\right) / \left(X_L - X_C\right)$$

Therefore for given sending and receiving end voltages and phase angle δ between them, the power transfer is more with the SC than without it as shown in Fig. 2-3. Thus series compensation leads to greater interchange of power and hence the synchronising power flow during transient conditions and thereby enhancing stability[20]. SC offers an effective and economical means of improving voltage regulation, steady-state and transient stability limits and hence permits the line to carry more power[21,22].

SCs are also suited to radial distribution line where light flicker is encountered due to rapid and repetitive load fluctuations[20].

The compensation of total inductive reactance by SC will lead to resonance at normal frequency hence inpractice only about 60-70% of the inductive reactance is compensated[1,14].

(iii) Shunt compensation:- It is done by using the shunt capacitor (or synchronous condenser) particularly in distribution line and shunt reactors at different locations of long transmission line.

In long distance a.c. transmission line the stability can be improved by shunt reactors in addition of SCs[24]. Two main problems encountered in the use of long EHV lines are the growth of charging current under low load and lowering of the stability limit with increase in line length[25]. Shunt reactors improve the voltage profile hence control overvoltages on the line and compensate for the predominated line capacitive susceptance under low load, hence neutralize line to ground capacitance (C). Use of high MVAR rating reactors (as high as 360 MVAR) for EHV lines are in practice (e.g. on 420 KV interconnection between Norway and Sweden)[19].

CHAPTER - III

PROTECTION OF EHV TRANSMISSION LINE

PROTECTION OF EHV TRANSMISSION LINE

Upto certain line lengths conventional impedance relay give satisfactory performance, distinguishing between fault and load conditions (including power swings), based on the measurements of the magnitude of impedance of the line. But incase of longer lines the difference in impedance between load and fault conditions becomes less and it will be difficult to distinguish between these two conditions.[26]

Although there is little difference in the impedance magnitude during fault and load conditions on long lines but fortunately, a considerable difference in phase angle exists. During heavy loading conditions, the load current component tends to decrease the power factor angle of the impedance seen by the relay (load plus transmission line). Whereas, during a fault within the zone of protection, the line impedance, only up to the fault location appears to the relay. Which is highly inductive (power factor angle, $\phi = 80^{\circ}$-88° for EHV lines)[1] as in Fig. 3-1.

The most positive and reliable type of protection is by pilot-wire method i.e., to compare the current entering the circuit with the current leaving it. But in EHV line, lengths of transmission lines make this principle uneconomical.[27] Similarily overcurrent relays can be used only where minimum fault current exceeds the maximum load current.

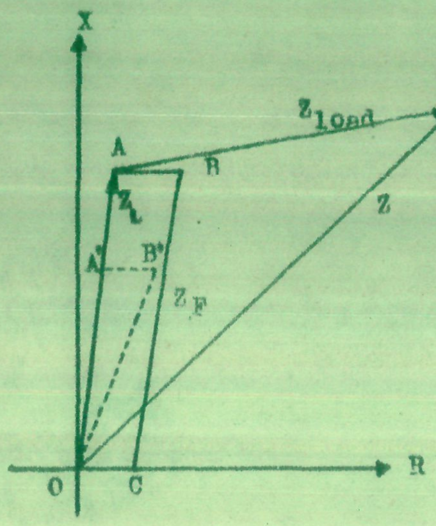


Fig. 3- 1, OABC is fault area.

OD = Z, impedance seen by relay.

OA = Z_L, total line impedance.

OA' = Z_1, line impedance upto fault

OB' = Z_F, fault impedance.

A'B' , arc resistance.

Z_{load} , the load impedance at receiving end.

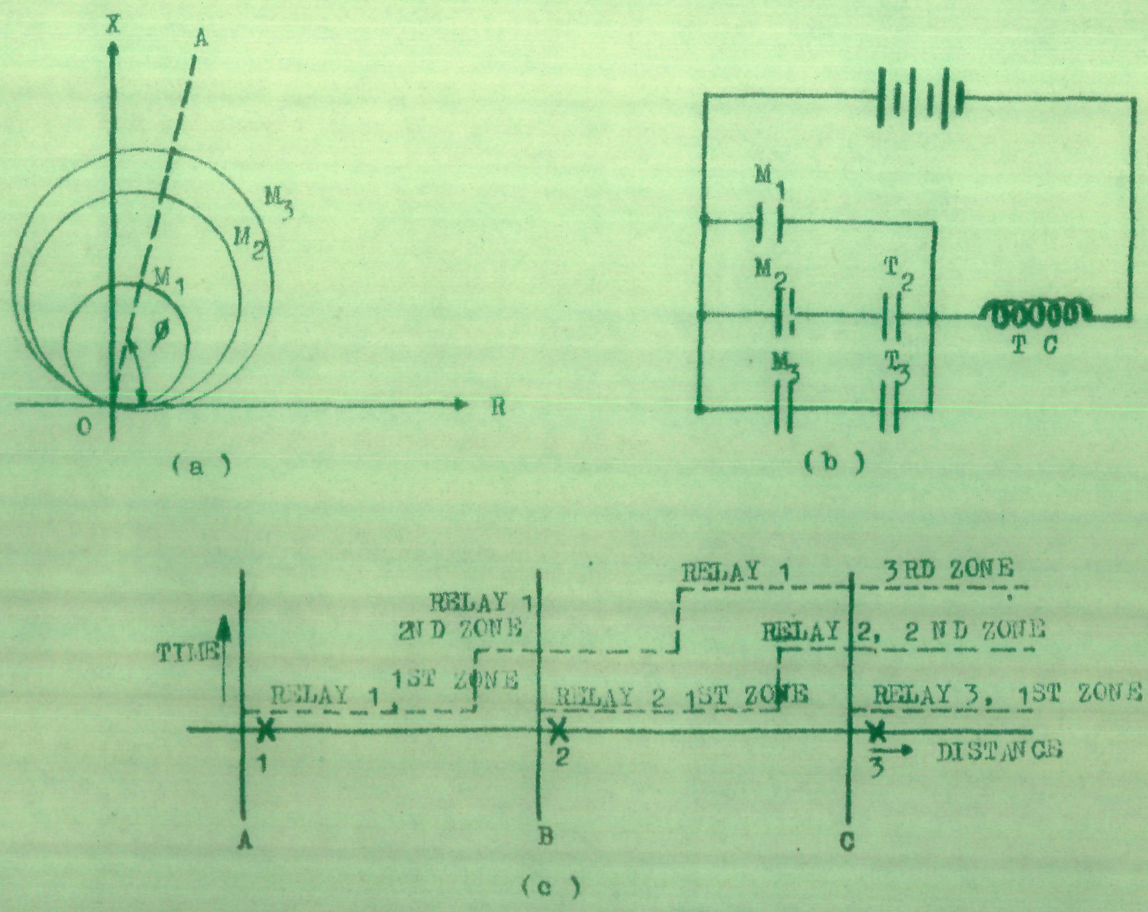


Fig. 3-2, THREE-STEP CHARACTERISTIC OF MHO - DISTANCE RELAY. (a) TRIP CIRCUIT & CHARACT. (b) TRIP CIRCUIT & (c) TIME DISTANCE SCHEME

The MVA level of the fault is very high in EHV lines because it is related to the square of the KV rating. It is further increased by the reduction of series impedance due to SC and bundling the conductors. At 400 KV the fault level goes as high as 35000 MVA.[28] Therefore faults on EHV links must be cleared as fast as possible to prevent the system from becoming unstable. There is very little possibility of improvement in electromagnetic relays in this regard. The experience shows the semiconductor relays are more reliable and fast in operation as compared to electromagnetic relays. Due to the absence of moving parts the response is quick and maintainance is reduced to a periodic check only.

Three-step zonal protection:

Since the reach of a distance relay cannot be adjusted very accurately. There is a need of second distance measuring unit to take care of faults at the far end of the protected line section near the next bus. Therefore the transmission line having successive line sections can be protected by means of three-zone distance protection scheme. By such schemes, quick protection can be obtained and back-up protection of the sections as well as adjoining lines/bus can also be provided.[29] Reffering to Fig. 3-2, the distance relay 1 at station A, has a 3-step characteristic. The relay has one conventional instantaneous mho element (with operating time T_1) and two mho elements with time delays T_2 and T_3 respectively.

The first element M_1 covers about 80-90% of the first line section AB. The second element M_2 covers the remaining portion of section AB and also 40-50% of next section BC to provide back-up protection with time delay T_2. The third mho element M_3 covers the entire line. The elements M_1, M_2 and M_3 pick up simultaneously for fault in the first zone. But the fault is cleared after time T_1 by element M_1, since its operating time is minimum. Elements M_2 and M_3 alongwith timers provide back-up protection.

Carrier Assisted distance protection:-

For long lines carrier-pilot relaying is more reliable and cheaper than pilot-wire relaying, even though the terminal equipments are more expensive and complicated. Power line itself is used as a channel for carrying information between two ends of the transmission line. There are various modes of carrier protection.

(i) Carrier transfer (Intertripping):- In this case carrier signal transmitted to the other section of transmission line for simultaneous tripping. Stepped time distance relays R_A and R_B are arranged at the both ends and towards protected section of the transmission line as shown in Fig. 3-3(a). If the fault (F_1) occurs in the middle of the section, the distance relays R_A and R_B at the both ends trip simultaneously in time T_1 of the first step. If fault (F_2) occurs near the

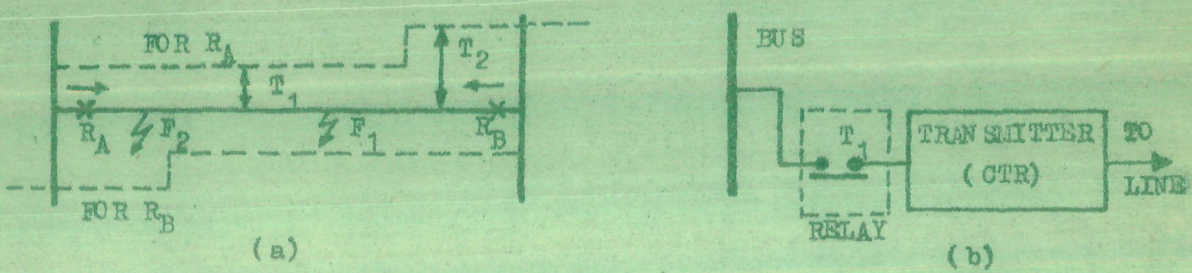


Fig. 3-3, (a) CARRIER TRANSFER CHARACTISTIC AND (b) CARRIER STARTING FOR TRANSFER SIGNAL.

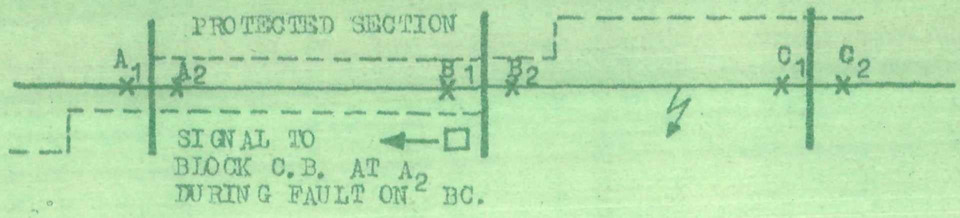


Fig. 3-4, DIRECTIONAL COMPARISON (CARRIER BLOCKING)

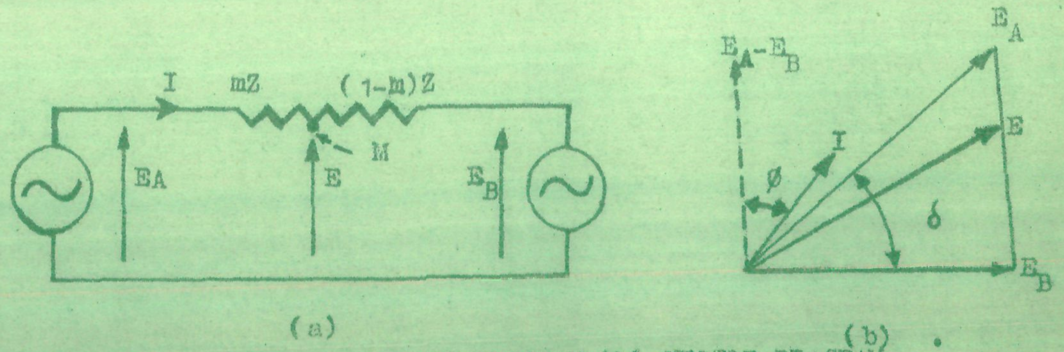


Fig. 3-5, TWO M/C SYSTEM (a) CIRCUIT DIAGRAM (b) VECTOR DIAGRAM.

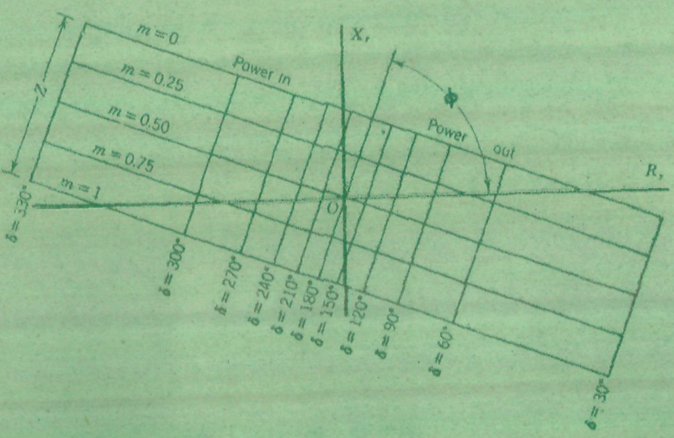


FIG. 3-6 Loci of impedance $R_r + jX_r$ "seen" by distance relays during swinging or out-of-step conditions on the two-machine system of Fig 3-5 with $E_A = E_B$.

end of the protected section (i.e., near R_A), the relay R_B will operate in time T_2 whereas relay R_A, nearer to the fault location will operate in time T_1 resulting in non-simultaneous opening of circuit breakers (CB) at both the ends. This is not desirable from stability and auto-reclosure considerations. Therefore the nearer relay R_A is made to send a carrier signal to the remote end relay (R_B) through carrier transmitter (CTR) to bring about simultaneous tripping of the CB's at both ends, as shown in Fig. 3-3 (b).

(ii) Carrier Blocking scheme (Directional comparison method):

The direction of fault power at two ends of the protected line is compared by means of directional relays. Under external fault the direction of flow of power is same at both the ends. While in case of internal fault the direction of the power flow will be reversed and inwards at both ends of the protected section. In this case provision is made to prevent the tripping of CB's for faults on next section and distance step is arranged to over-reach (about 20%) of the next section, as shown in Fig. 3-4. If fault occurs in adjacent line BC, the directional relay at B_1 will acutate and it will send blocking signal to Station A. Therefore the tripping of CB's at A_2 and B_1 is blocked. If fault occurs in section AB no signal is sent to block tripping of A_2 and B_1. The carrier is transmitted only during fault conditions and is used only to prevent tripping in case of an external fault. Therefore in case of internal fault the carrier channel (faulty section) does not pose any problem to the relays to clear the fault.[30]

Effect of swinging and out-of-step operation on Power System:

Power swings are surges of power due to the oscillation of generators with respect to each other which may occur because of changes in load, switching or faults. When two or more synchronous machines or group of machines swing with respect to one another or lose synchromism the relays are readily affected and false tripping of unfaulted or healthy lines may occur. Which would lead to cascaded tripping or failure of whole power system. Such situations arises mainly for long lines which are heavily loaded and are operating at or near the stability limit.

Analysis of the effect of swinging and out-of-step conditions upon relays:

When two machines or group of machines are running out of step (or lose synchronism), there is a moment in each slip cycles at which the phase difference of their internal voltages is 180°, and the conditions is similar to three phase short circuit approximately midway between machines. i.e., the line voltages at the apparent fault point becomes zero and line currents are high. As a result, the relays can see a fault although there is none. Similarly if the two machines or group of machines are swinging (after clearing a severe fault), even though they do not lose synchronism with one another, there may be moments when the angular displacement between their internal voltages is so great that electrical conditions in the network approach those of a three-phase short circuit closely enough to deceive the relays.

The effects of swings and out-of-step operation on relays of the two machine system (Fig. 3-5) are shown in Fig. 3-6. Here E_A and E_B are voltages behind transient reactance. E_A leads E_B by the variable angle δ and current is $I = (E_A \angle\delta - E_B \angle 0^\circ) / Z$. Where Z is the impedance of connecting circuit (line) including the transient reactances of two machines. The total impedance, Z is devided by relay location M into two parts, mZ and (1 - m) Z, where m is real number less than 1. At point M the voltage $E = (1-m)\, E_A \angle\delta + m\, E_B \angle 0^\circ$.

The impedance "seen" by the distance relay at M is $Zr = E/I$. If E_A and E_B are constants and δ is varied, the locus of Zr in the complex impedance plane is either a straight line (if $E_A = E_B$), as shown in Fig. 3-6, or a circle (if $E_A \neq E_B$).

If the two generators are in phase with each other, the current is zero, and therefore, the apparent impedance is infinite; but if the generators are 180° apart, the voltage becomes zero at middle of the line, and therefore there appears

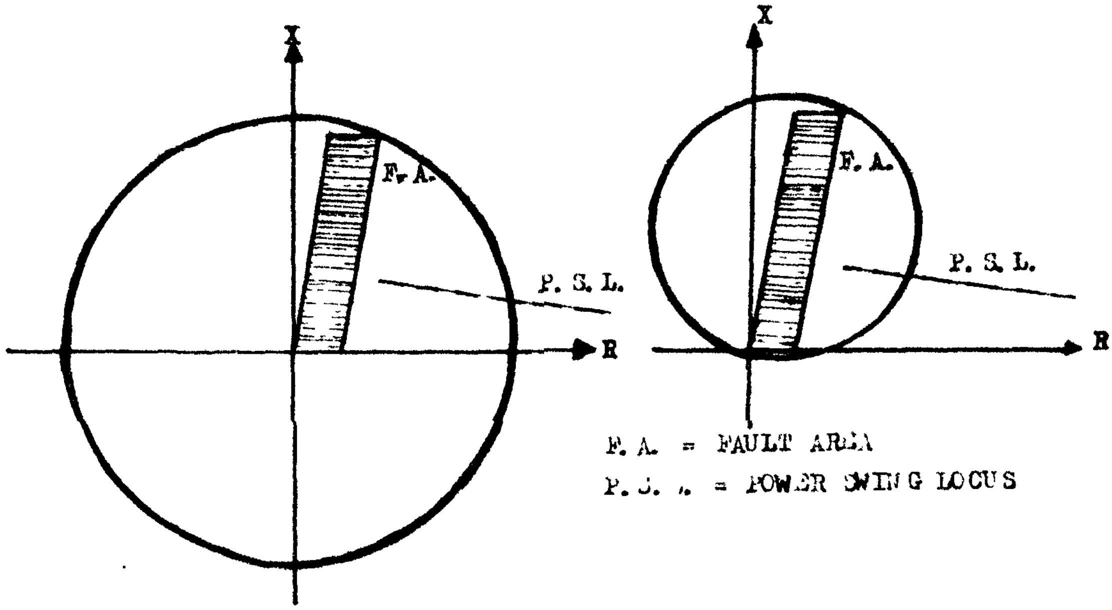


Fig. 3-7, OHM AND MHO CHARACTERISTICS WITH POWER SWING LOCUS.

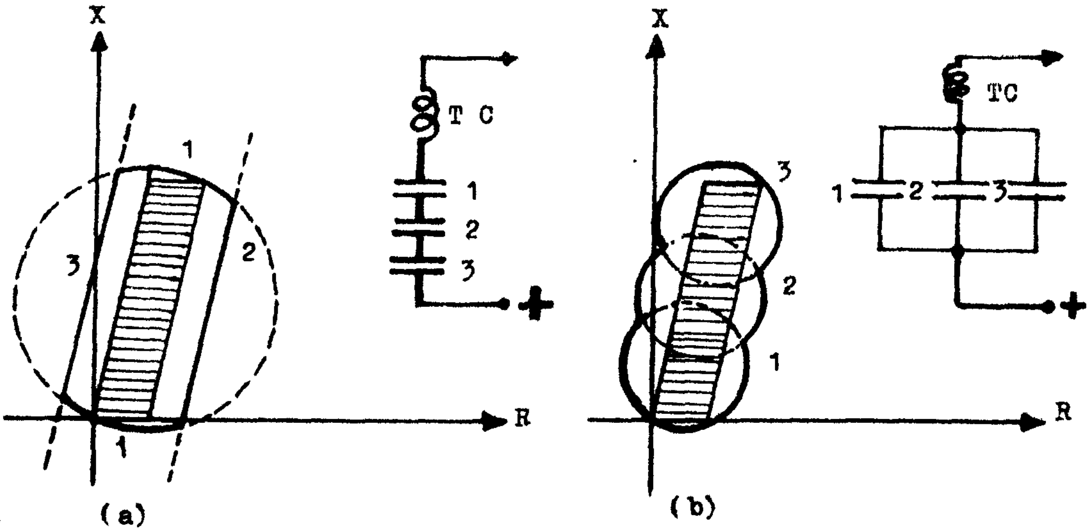


Fig. 3-8, (a) MHO CIRCLE WITH BLINDERS (b) 3-OVERLAPPING MHO CIRCLES.

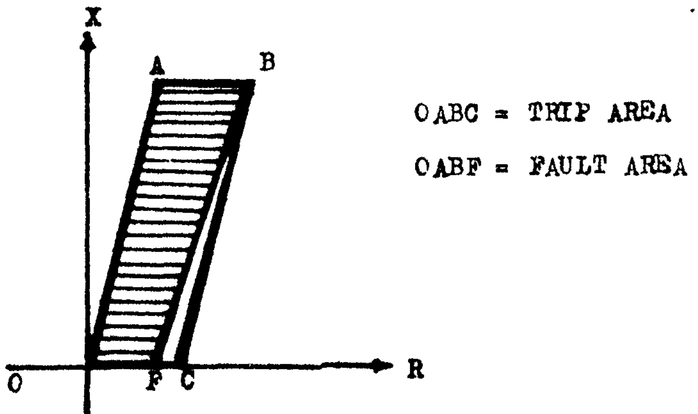


Fig. 3-9

to be a three phase short circuit at that point ($m = 1/2$).

For long lines, as their line impedance is large therefore the diameter of ohm or mho characteristics circles of the distance relays will be large. Hence these distance circles will cover unwanted large trip area on impedance plane. Therefore these units will be more vulnarable to power swings than short lines (Fig. 3-7).

Multilateral Quadrilateral Characteristics:

Due to above mentioned reason, to reduce unwanted trip area, several multilateral characteristics were suggested for long transmission line. Few of them use blinders in conjunction with other distance relays as shown in Fig. 3-8(a).[26] Whereas other use two or more overlapping characteristic circles of mho and off-set mho units with parallel contacts as shown in Fig. 3-8 (b).[1,31] But even these modified characteristics cover a significant unwanted trip area and several units are needed in addition. Therefore multiinput quadrilateral characteristic is much more attaractive since it covers approximately only the trip area on Z-plane. The characteristic is realized by comparison of input signals to obtain several boundry characteristics with a single comparator as shown in Fig. 3-9.

CHAPTER - IV

DISTANCE RELAY CHARACTERISTIC SUITABLE FOR SERIES COMPENSATED LINES

DISTANCE RELAY CHARACTERISTIC SUITABLE FOR SERIES COMPENSATED LINES

Conventional distance relays with circular characteristics are vulnerable to power swings, owing to the wide operating region in R-X plane as discussed in previous chapter. Hence most desirable characteristic for an EHV line is a quadrilateral one, which covers only fault region on R-X plane by a narrow characteristics.

In a power system the impedance of a line increases linearly with distance. The line length is restricted by its voltage level due to stability as well as economic reasons[1]. The necessary line length would require very high voltage for economical operation, its effective length (in respect of impedance) may be shortened by compensation techniques (as discussed in Chapter II). Therefore, EHV lines are often equiped with series capacitors. They are provided either at the ends or at the middle of the transmission line. Spark-gaps, provided across the capacitor, generally flash-over during faults and under abnormally high current conditions to protect the capacitor against over-voltages. During power-swings, the high value of current may cause flash-over of the spark gaps thereby shorting the capacitor when it is needed most. Proper spark-gap setting may avoid this unwanted operation. However, in that case, the spark-gap may not flash-over during a fault with low value of short circuit current.

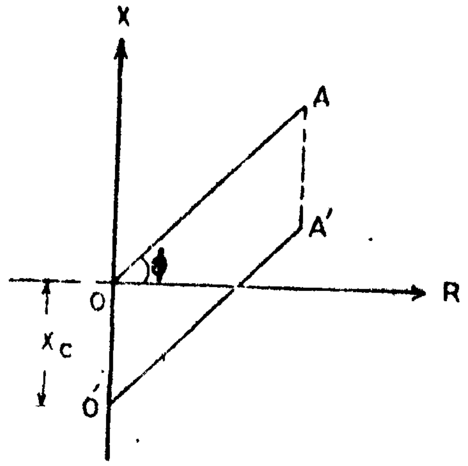


FIG.41.

Impedance seen by relay with the series capacitor at sending end.(OA = transmission line impedance, and its phase angle, $\phi = \tan^{-1} X_L/R_L$).

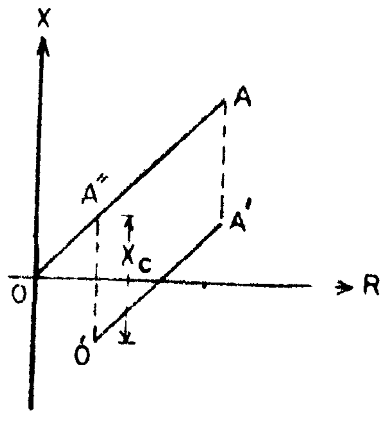


FIG.42.

Impedance seen by relay with series capacitor at an intermediate location.

The impedance seen by a distance relay changes abruptly for locations just after the series - capacitor connection. But, if the spark-gap flashes-over, the capacitor being shorted, no abrupt change in the impedance is seen by a distance relay.

Insertion or the shorting of the series-capacitor in the transmission line, being dependent on the magnitude of fault current makes the protection of the line difficult. Therefore, a line with series capacitors require a special impedance characteristic.

Desired distance relay characteristic for a series compensated line

Figure 4-1 shows the impedance seen by a distance-relay with the series capacitor connected at the sending end. OA is the impedance of the protected zone when the series-capacitor is shorted. The impedance seen by the relay varies along OA with the distance when series-capacitor is shorted. Whereas the impedance varies along O'A' with the series capacitor in the circuit. In this diagram the arc and earth-resistances are neglected. Lines OA and O'A' are parallel to each other. Figure 4-2 shows the variation of the line-impedance with the series-capacitor at some intermediate location along the line.

Including the effect of the arc and earth resistances the desired quadrilateral characteristic of the distance-relay with the SC at the sending end is shown in Fig. 4-3. Actually they are two different relay characteristics namely OABC and O'A'B'C'. But the corresponding lines are parallel to one another. For a long

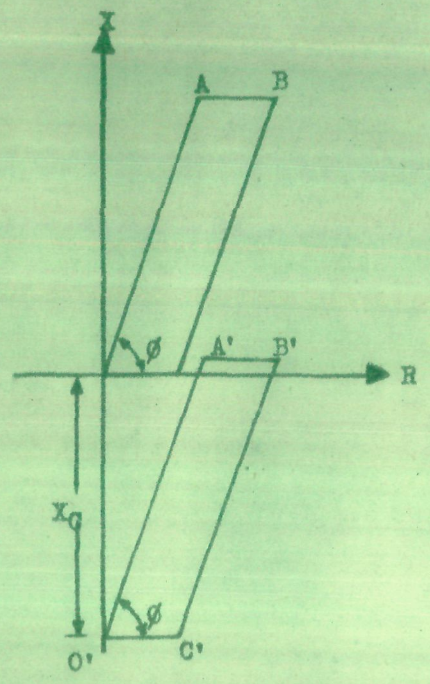


Fig. 4-3 Proposed characteristic with SC at SE.

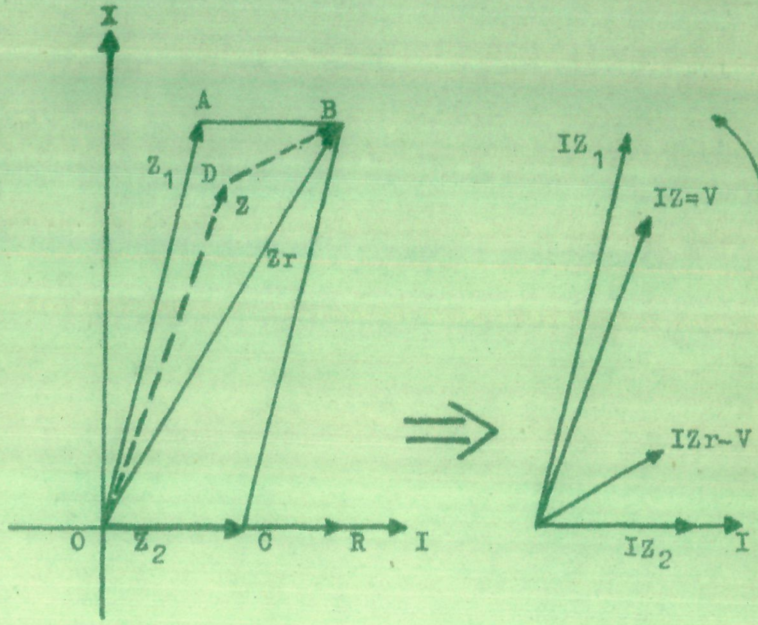


Fig. 4-4 Replica impedances for the quadrilateral characteristic on R-X plane and corresponding phasor inputs to P.S.D. (I is reference phasor)

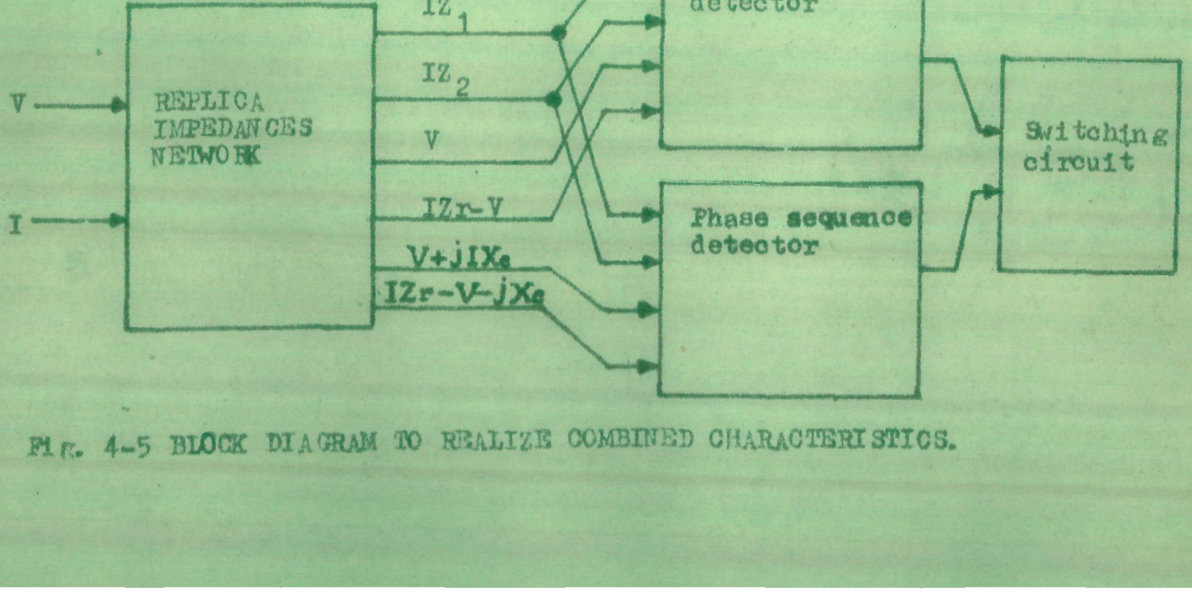


Fig. 4-5 BLOCK DIAGRAM TO REALIZE COMBINED CHARACTERISTICS.

transmission line, the arc-resistance is small in comparision to the total impedance of the line. Therefore, the line AB never touches the extented portion of O'A'. Intersection of the line AB with extended portion of O'A' indicates high over-reach of the relay with the series-capacitor not shorted during a fault. Therefore, the two characteristics OABC and O'A'B'C' combined together become the desired distance relay characteristic with the SC at the sending end. Similarly, the characteristics for an intermediate location of the SC may also been obtained. The combined characteristic shown in Fig. 4-3 is superior to the conic characteristics.

Phase sequence comparision for Quadrilateral Characteristic:

In Fig. 4-4, impedances OA and OC are Z_1 and Z_2 respectively. Impedance OB is Zr, the fault impedance OD is Z (= V/I) and impedance DB is (Zr-Z).

If the fault impedance Z lies within the zone OABC, it can be proved very easily that either the phase sequence (OA, OD, DB, OC) or (OA, DB, OD, OC) is maintained.[10] Therefore four inputs viz. IZ_1, V, (IZr - V) and IZ_2 are fed to four input phase sequence comparator.

The comparator is so designed that the output is obtained only when the phase sequence is either $\left[IZ_1,\ V,\ (IZr-V),\ IZ_2 \right]$ or $\left[IZ_1,\ (IZr - V),\ V,\ IZ_2 \right]$. Thus the area inside the quadrilateral OABC indicates the operating zone.

Area O'A'B'C' is identical with OABC with the origin shifted to O' from O. Four separate inputs viz., IZ_1, $(V+jIX_C)$, $(IZr - V - jIX_C)$ and IZ_2 are fed to a second four-input phase-sequence comparator. To obtain the operating zone within the area O'A'B'C' the phase sequence must be either $\left[IZ_1, (V+jIX_C), (IZr - V - jIX_C), IZ_2 \right]$ or $\left[IZ_1, (IZr - V - jIX_C), (V + jIX_C), IZ_2 \right]$.

Block diagram showing the inputs and comparators for obtaining the combined characteristic of Fig. 4-3 is shown in Fig. 4-5.

On the basis of the block diagram a distance relay may be designed either with analog signals or with the help of microprocessor.

The basis principle mentioned above may be extended to obtain several other characteristics for the SCs at some intermediate locations and multi-step distance relay characteristic (by using over laping quadrilaterals of different sizes).

CHAPTER - V

REALISATION OF QUADRILATERAL CHARACTERISTIC

REALISATION OF QUADRILATERAL CHARACTERISTIC

The realization process of a quadrilateral characteristic can be devided into three steps, namely

(i) Realization of various inputs to the phase sequence detector (P.S.D.) from CT and PT outputs.

(ii) Realization of a four input phase sequence detector which gives binary output.

(iii) Realization of output switching circuit which can energize the trip coil of circuit breaker and also gives visual and audible alarms on receipt of trip signal from P.S.D.

(i) Realization of inputs:

The required inputs can be obtained using passive elements only as shown in Fig. 5-1. But from the realization point of view, it is not attractive since the realization of inductance of required value and quality creates problem, apart from its weight and size. Therefore the inputs are realized with Active-RC elements using operational amplifiers (OP-AMP.) as an active device. Figure 5-2 shows the arrangement for generation of four inputs i.e., IZ_1, IZ_2, V and IZr-V to the P.S.D.

As shown in the phasor diagram (Fig. 5-3), the phasor KIZ_1 (where K is a real number and less than one) can be varied from 0° to 180° with respect to IZ_2, keeping its magnitude as

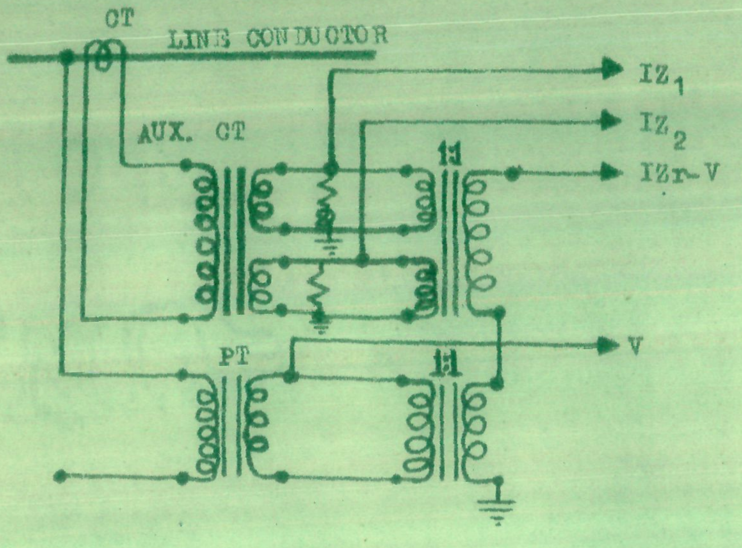


Fig. 5-1, REALIZATION OF INPUTS FROM PASSIVE DEVICES FOR P. S. D.

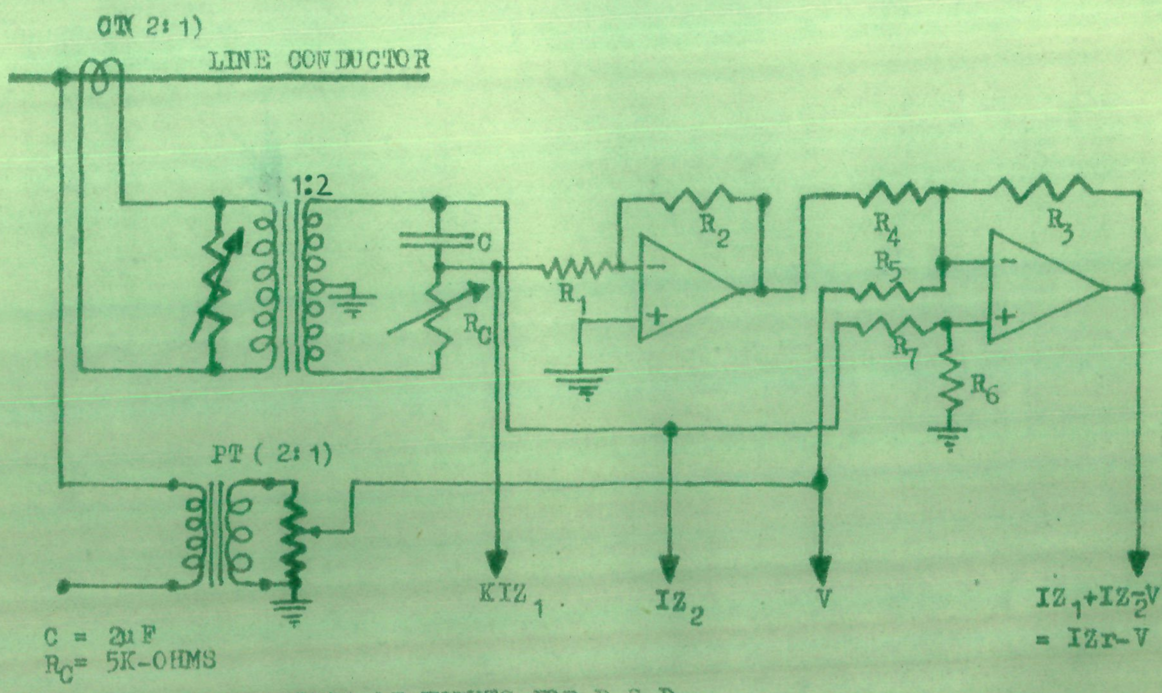


Fig. 5-2, REALIZATION OF INPUTS FOR P. S. D.

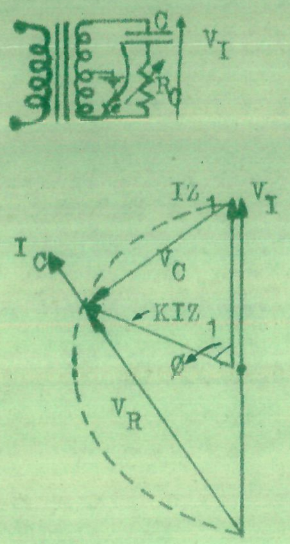
constant. It is to be noted that magnitude of KIZ_1 is equal to that of IZ_2 for any phase angle between them.

To obtain proper shape of the characteristic, magnitude of IZ_1 is kept as three times of magnitude of IZ_2, by amplification of KIZ_1 to IZ_1 ($K = R_1/R_2 = 1/3$; $R_1 = 5.1\ K\Omega$, $R_2 = 15 K\Omega$). Then by proper summation of IZ_1, IZ_2 and V, the fourth input $IZr - V$ is realized (where $IZr = IZ_1 + IZ_2$). All resistors in the summer circuit are 5.1 $K\Omega$ except R_5 which is equal to 10.2 $K\Omega$ (derivations and calculations are given in Appendix). All signal levels in the given network are kept low to avoid distortion due to saturation of OP-AMP at the time of fault when current I and hence IZ_1, IZ_2, etc. attain relatively high values.

(ii) <u>Phase sequence detector</u>:

To detect the phase sequence, among the four inputs, sharp pulses are formed by pulse forming circuit (P.F.C.), corresponding to positive zero cross-over instants of each input signals. The P.F.C. comprises of a zero crossing detector (Z.C.D.), differentiator and rectifier. Now the sequence among these pulses are obtained by AND, NOR, NAND gates and bistables using 7400 N and F7402PC IC Chips (pin connections and detailed circuit connections are given in Appendix).

The operation of pulse forming circuit (Fig. 5-4) is



C = 2µF

R_C = 5K-OHMS

Fig. 5-3, PHASOR DIAGRAM.

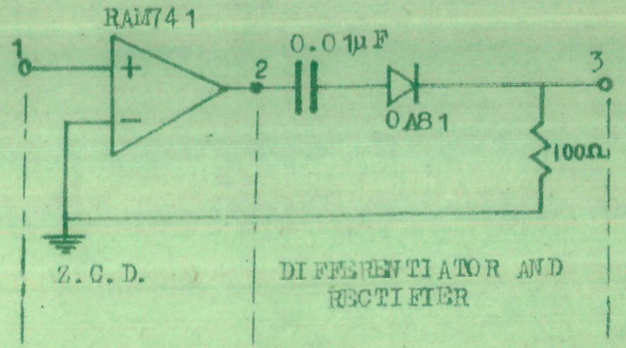


Fig. 5-4, PULSE FORMING CIRCUIT

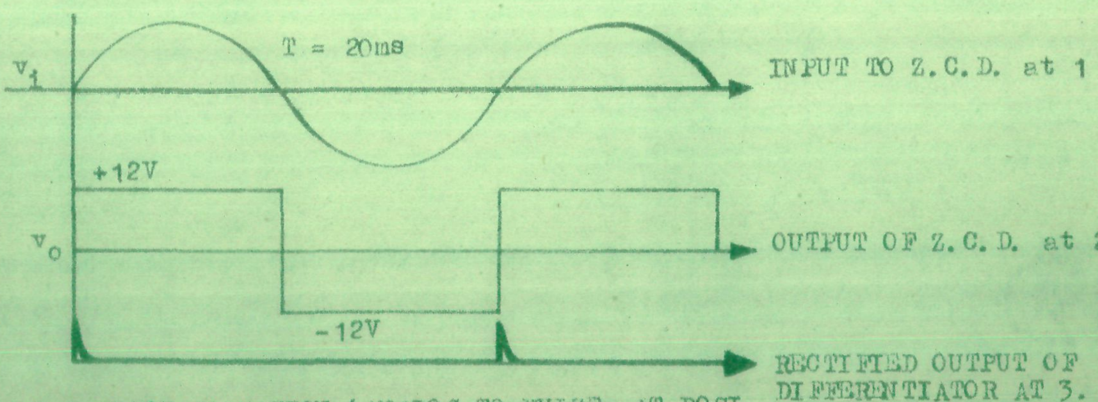


Fig. 5-5 PULSE FORMATION (ANALOG TO PULSE, AT POSITIVE ZERO-CROSS OVER).

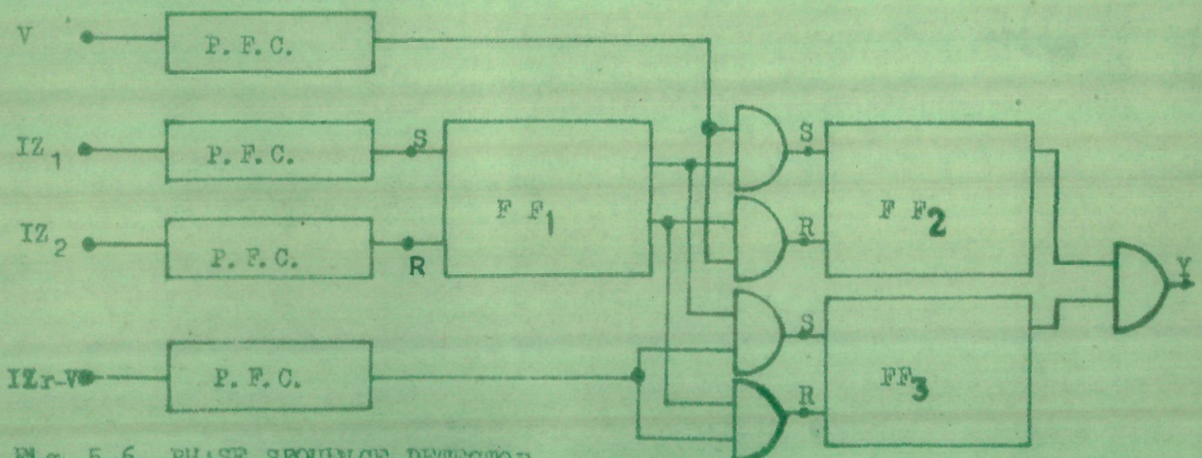


Fig. 5-6, PHASE SEQUENCE DETECTOR

demonstrated in the waveforms shown in Fig. 5-5. An OP-AMP, RAM741 is used in the open loop mode as Z.C.D., and a diode OA81, C = 0.01 μF and R = 100 Ω are used to realize a differentiator.

The four inputs used are KIZ_1, IZ_2 V and IZr - V. Using input KIZ_1 inplace of IZ_1 will not matter since it does not affect the zero cross-over instants. Now it is to be tested that whether the inputs are in a proper sequence required for operating condition or not. For operation the sequence should be either (IZ_1, IZr-V, V, IZ_2) or(IZ_1, V, IZr-V, IZ_2). Hence it is sufficient to check whether both V and IZr-V lie in between phasors IZ_1 and IZ_2 or not (such that they lag IZ_1 and lead IZ_2). This can be done by comparing separately V and IZr-V with IZ_1, IZ_2 and connecting the outputs ato an AND gate. The circuit diagram of phase sequence detector (P.S.D.) is given in Fig. 5-6. IZ_1 sets the output Q of FF_1 to high level and IZ_2 resets it to low level. If the pulse corresponding to V appears after setting the Q output of FF_1 to high level by IZ_1 (i.e., before it resetted by IZ_2) the output Q of second flip-flop, FF_2 sets to high level and remain high so long as the sequence remains IZ_1, V, IZ_2 as shown in Fig. 5-7 (a). On reversal of the sequence among IZ_1, V, IZ_2 the output of FF_2 resets to low value as shown in Fig. 5-7 (b). Similarly FF_3 sets its output Q to high level for phase sequence IZ_1, IZr-V,

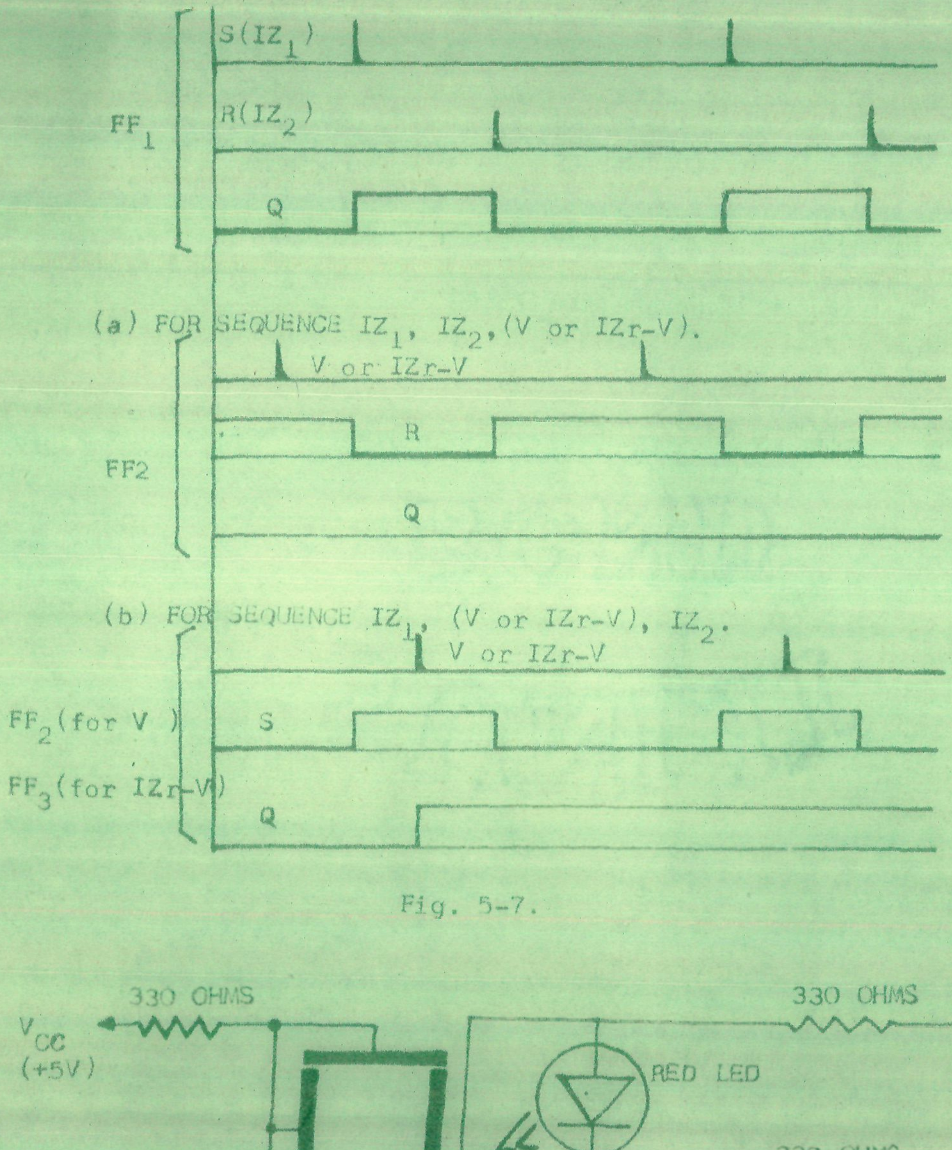


Fig. 5-7.

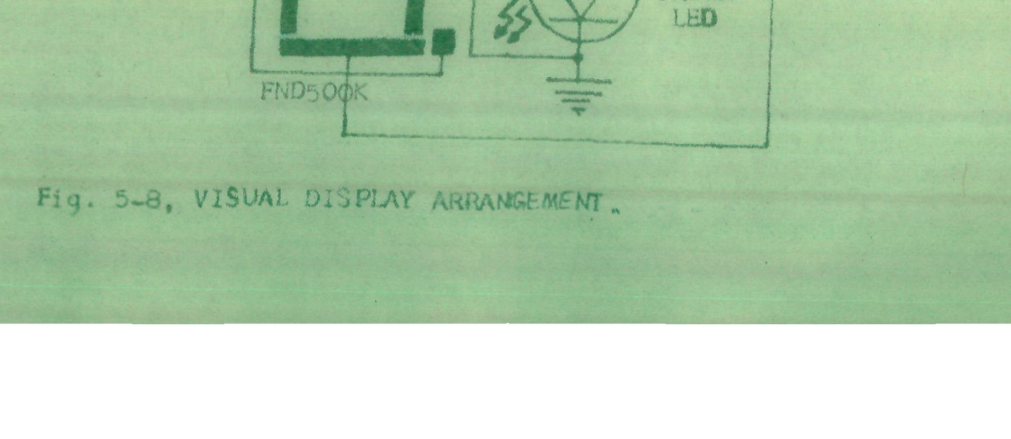


Fig. 5-8, VISUAL DISPLAY ARRANGEMENT.

IZ_2. Hence when both V and IZr-V lie in between IZ_1 and IZ_2, the final output Y of the P.S.D. is at high level.

(iii) <u>Output switching devices</u>:

The high level of the final output at Y available from the AND gate is about 4 volts. This has directly been used to drive seven segment display (FND500K) and two light emitting diodes (LEDs) as shown in Fig. 5-8. On detection of proper sequence i.e. at the time of fault, a red LED glows and the display writes F. (indicating a fault condition). Healthy condition i.e. normal condition (including the fault beyond the zone of protection) is indicated by a green LED and a symbol C. (i.e. clear) at the display. Provision is made for the extension of the final output Y. Hence this signal can also be applied to gate of a SCR with suitable buffer to energize the circuit breaker's trip coil and/or to give an audio alarm.

CHAPTER - VI

TESTING OF THE RELAY WITH ARTIFICIAL TRANSMISSION LINE

TESTING OF THE RELAY WITH ARTIFICIAL TRANSMISSION LINE

An oscilloscopic method was used to test the performance of the designed four-input phase sequence detector (P.S.D.) separately[32]. For this purpose, another four-input P.S.D. is fabricated (circuit diagram is shown in Fig. 6-1), which gives visual display of the sequence. The output of this test-P.S.D. is shown in Fig. 6-2, where each tip of the waveform corresponds to particular input. By variation of particular potentiometer setting (corresponds to particular input), sequence among the input phasors may be known. Three inputs, from a 3-phase auto-transformer and fourth from a phase shifting transformer were derived to test the performance of P.S.D. with test-P.S.D. The P.S.D. found to work properly and the output tally the output of test-P.S.D. Next, the operation of each P.F.C. was tested using CRO.

Finally performance of overall relay was tested with an artificial transmission line of medium length. It consists of eighteen π-section representing total 151.2 kms. length, each section having $R = 2.1$ ohms, $L = 21$ mH and $C = 0.08$ μF as shown in Fig. 6-4 and 6-5. The phase angle of the line impedance was 73°. The zone of protection was extended upto 17th section of the artificial transmission line, leaving last section for simula tion of faults outside the zone of protection. The arrangement i shown in Fig. 6-6.

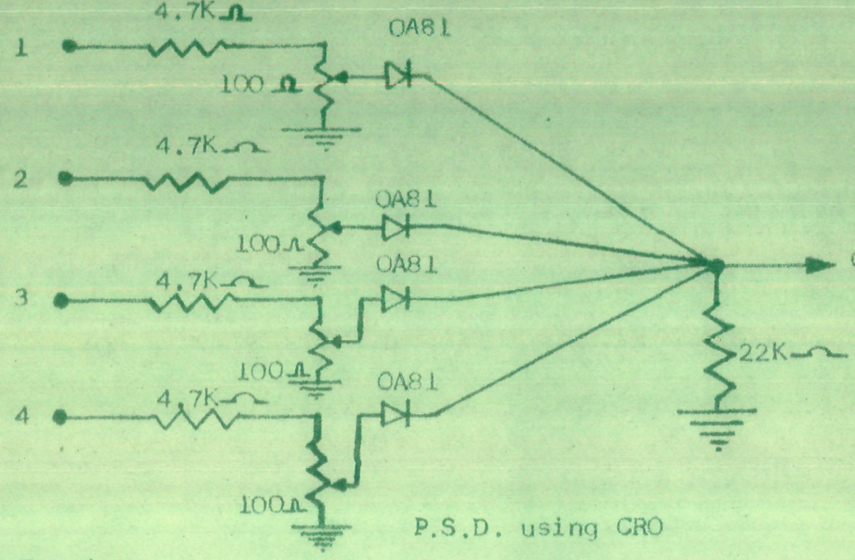


Fig.6-1,

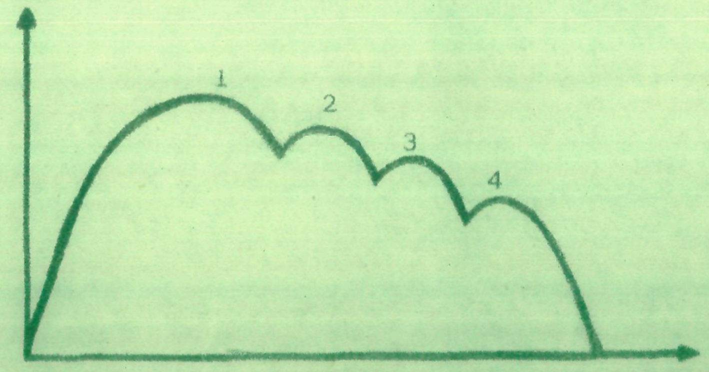


FIG.6-2, OUTPUT WAVE FORMS

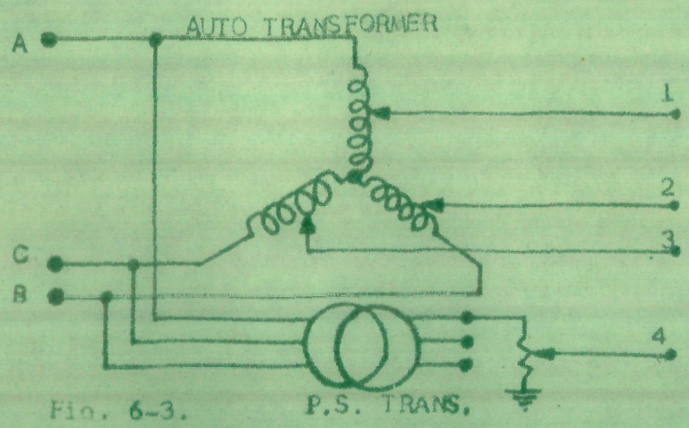
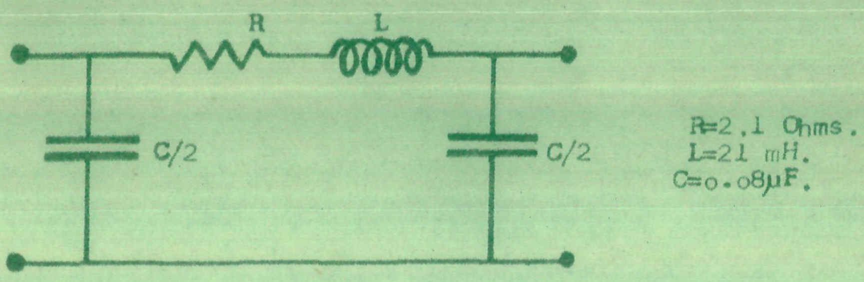


Fig. 6-3. P.S. TRANS.



ONE SECTION OF ARTIFICIAL TRANSMISSION LINE
Fig.6-4

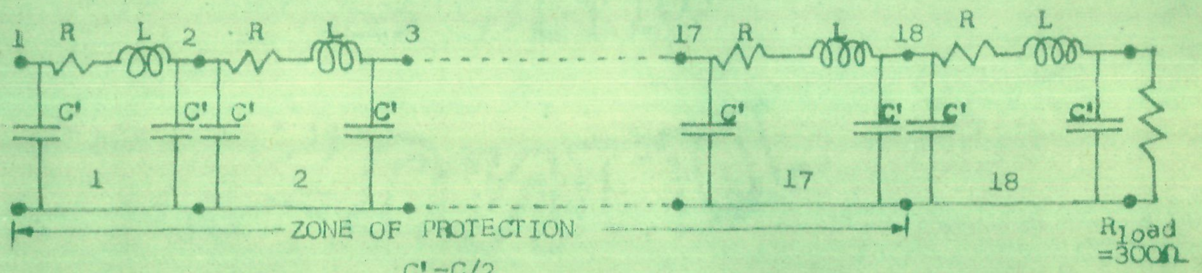


Fig.6-5 ,ARTIFICIAL TRANSMISSION LINE AND RECEIVING END LOAD

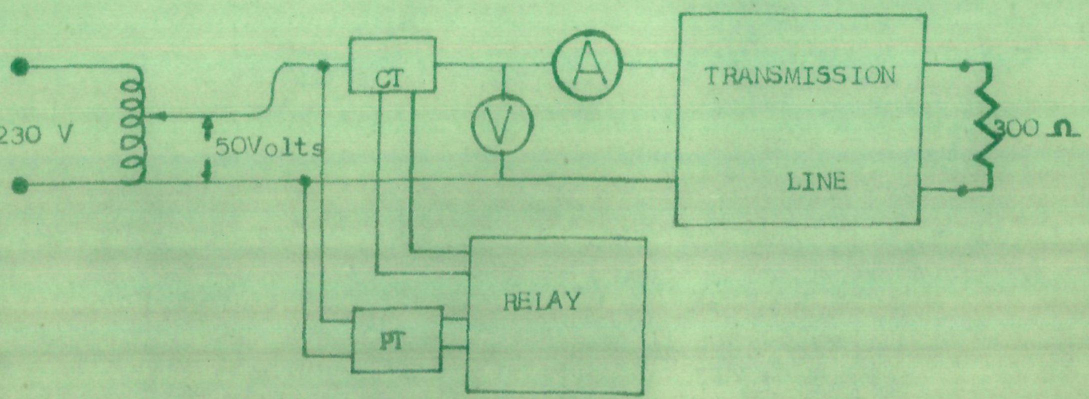


FIG.6-6,TESTING ARRANGEMENT.

To realize proper quadrilateral characteristic suitable to this line, the phasor IZ_1 was adjusted with the help of R & C elements such that it leads slightly the phasor V, for a fault at the boundary of the protected zone (i.e. at the end of 17th section). The magnitude of V was adjusted and made equal to magnitude of IZ_1.

Under normal condition with a 300 ohms resistive load connected at receiving end of the line, a “C” symbol was observed at the display alongwith glowing green LED. This indicated healthy condition. With the help of a dual trace CRO the sequence among the inputs were observed. It was found that in this condition while the phasor V lie in between IZ_1 and IZ_2, phasor IZ_r-V did not lie between them. Same results were obtained for a fault at the end of 18th section (i.e. outside the zone of protection).

In case of unloaded or lightly loaded line, both the phasors V as well as IZ_r-V did not lie in between IZ_1 and IZ_2 and therefore, glow of green LED and symbol “C” was observed.

For a fault within the zone of protection (1st to 17th section), the phasor IZ_r-V was found to lie in between IZ_1 and IZ_2 with phasor V lying as usual between them. Therefore a proper sequence between the inputs was obtained. A “F” symbol at the display and a red LED indication were observed at the relay output.

Most of the waveforms observed on the CRO during each stage of testing were preserved and shown by the photographs given in the Appendix.

CHAPTER - VII

C O N C L U S I O N

CONCLUSION

Scope of further works:

The principle discussed in designing of the relay can also be utilized in different ways to obtain various other functions.

(i) Reactance Relay:- A reactance relay can be realized easily using single three-input P.S.D. The phasor diagrams and the sequence of the inputs for fault and healthy conditions are shown in Fig. 7-1(a) & (b) respectively. The phase sequence under trip condition will be (IZ_1, $IZr-V$, IZ_2). The proposed circuit to realize inputs may be as shown in the Fig. 7-2.

(ii) Phase Comparator Relay:- The principle with some modification can be used to make a phase comparator or directional relay which gives output signal when the phase difference between two inputs exceeds the rated value. The comparator also gives indication about relative phase position (leading or lagging) as shown in Fig. 7-3(a). The range of the phase comparator is less than $\pm 90^\circ$ (leading or lagging), however, it can be extended to $\pm 180^\circ$ by applying one of the input at inverting terminal of OP-AMP in Z.C.D. instead of non-inverting terminal. A passive RC phase shifter (P.S.) as shown in Fig. 7-2 or active-RC phase shifter can also be used. The arrangement is shown in Fig. 7-3(b).

(iii) Phase Angle Meter:- A phase angle meter can be made using the same relay principle. The output may behave in analog or

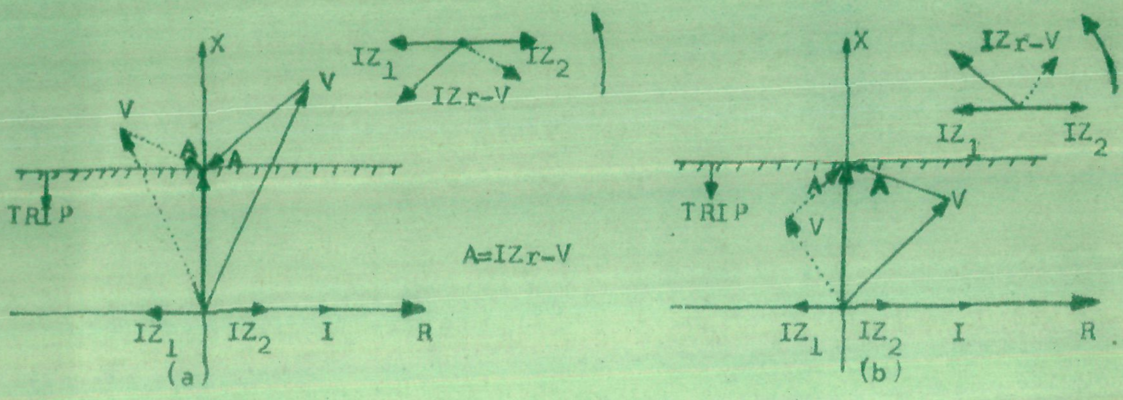


Fig.7-1, REACTANCE RELAY PHASOR DIAGRAM(a)NO TRIP& (b)TRIP CONDITIONS.

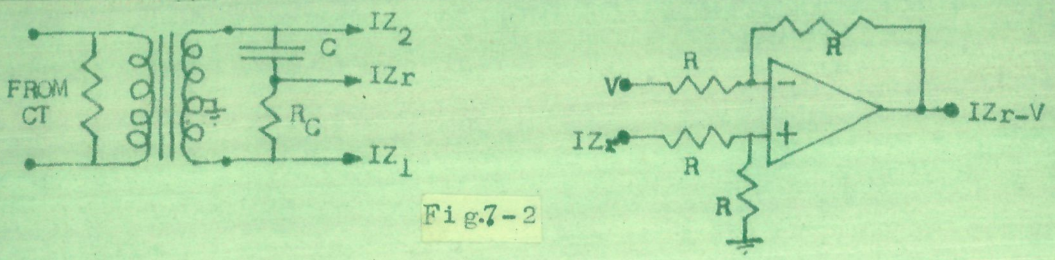


Fig.7-2

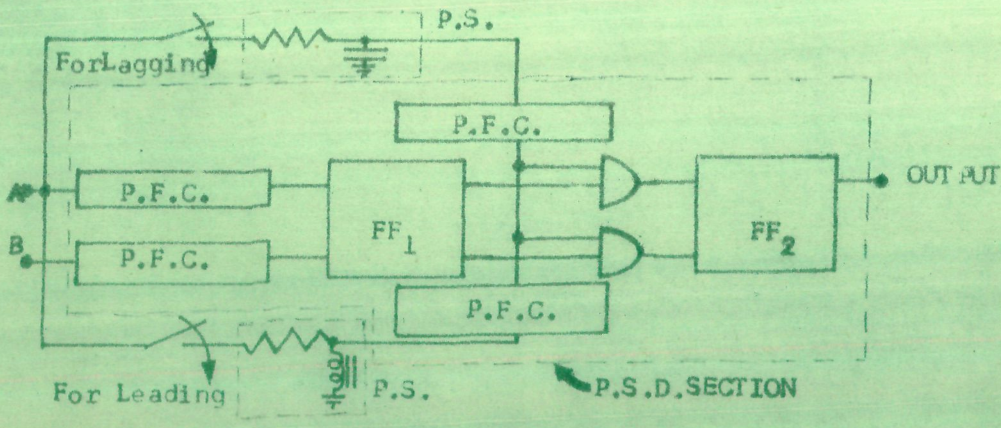


Fig.7-3(a)PHASE COMPARATOR RELAY.

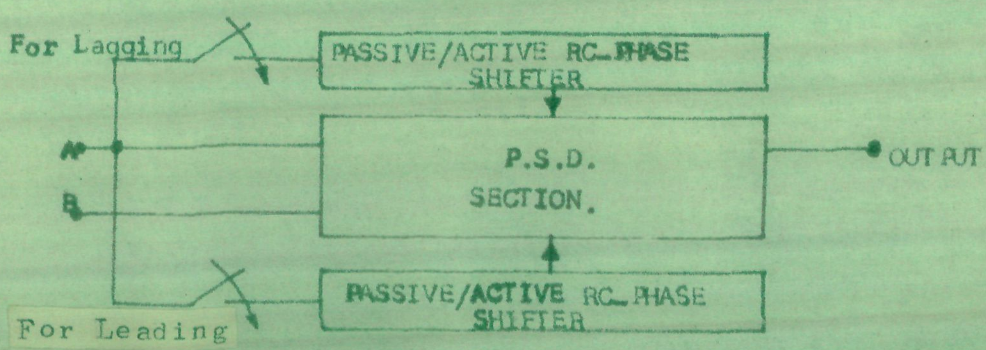


Fig.7-3(b). PHASE COMPARATOR RELAY.

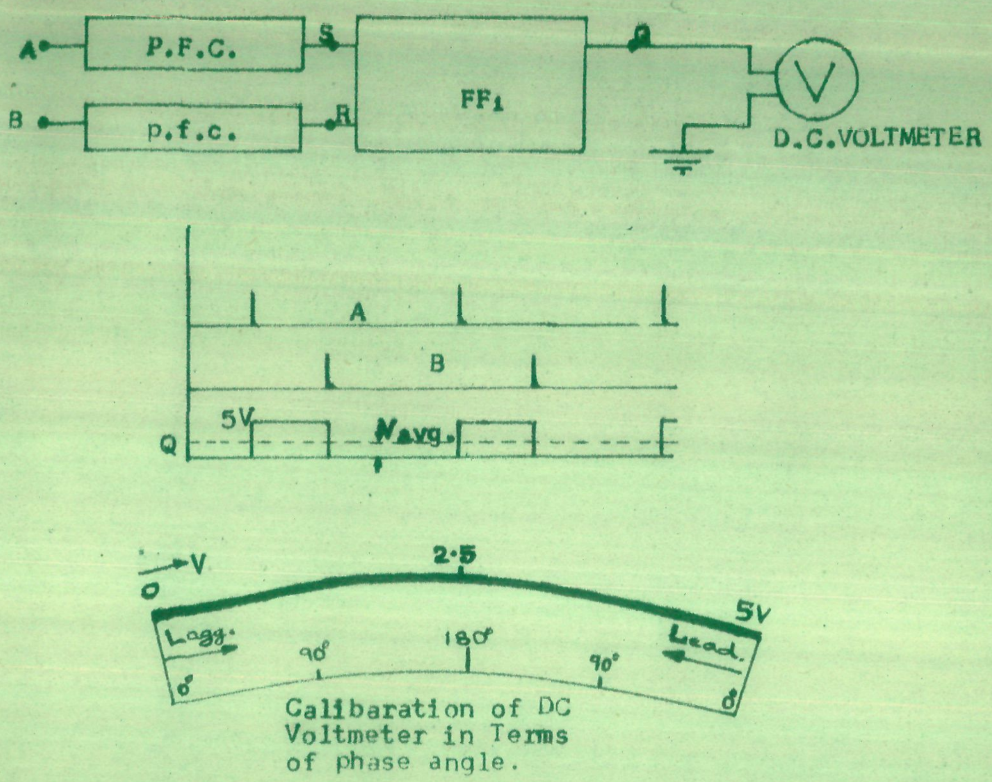


Fig. 7-4, ANALOG PHASE METER.

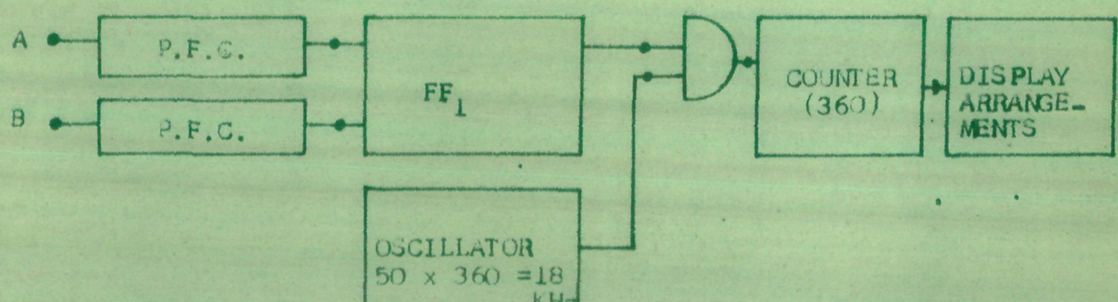


Fig. 7-5, DIGITAL PHASE METER.

digital form. A scheme with analog output shown in Fig. 7-4 and that for digital output is shown in Fig. 7-5. The phase difference corresponds to duration of high level at the output 'Q' of flip-flop FF_1. A counter can be used to count the number of pulses from an oscillator in this duration. Each pulse of oscillator corresponds to one degree. By proper arrangement of decoding and display etc.[33] the phase difference can easily be measured.

Concluding remarks:

A complete solid-state relay is designed to realize a quadrilateral characteristic suitable for series compensated EHV lines. The design procedure and detailed experimental results are also given. The characteristic of the relay can be modified to suit any particular transmission line with the help of various settings available. The time of operation of the relay is less than one cycle time (i.e. 20 m sec.).

Several modifications to existing relay also suggested to use it for some other useful purposes.

A P P E N D I X

APPENDIX

Calculation for Selection of resistances for summer and amplifier.

(i). For the amplification of the phasor KIZ_1 to IZ_1 (where $K = 1/3$)

$$R_1/R_2 = K = 1/3 \quad \text{or} \quad R_2 = 3\,R_1$$

If $R_2 = 15$ K-ohms = $R_1 = 5$ K-ohms, therefore $R_1 = 5.1$ K-ohms and $R_2 = 15$ K-ohms selected.

(ii). From the Fig. 8-1, for the summer circuit.

$$V_0 = K_1V_1 - K_2V_2 - K_3V_3$$

Let $K_1 = K_2 = K_3 = 1$

then $V_o = V_1 - V_2 - V_3$

Since $V_o = A\,(V_n - V_i)$ where A is gain of OP-AMP.

Applying Kirchoff's current Law (KCL) at inverting terminal of OP-AMP.

$$V_i\ (G_5+G_4+G_3) = G_3V_0 + G_5V_2 + G_4V_3$$

Where G represents conductance of the resistance.

Therefore, $V_i = (G_3V_0 + G_5V_2 + G_4V_3)\ /\ (G_5 + G_4 + G_3)$

Applying KCL at non-inverting terminal of OP-AMP.

$$V_n\ (G_7 + G_6) = G_7V_1$$

Now $V_0 = A\ \ G_7V_1/(G_7+G_6) - (G_3V_0+G_5V_2+G_4V_3)/(G_3 + G_5 + G_4)$

$\Longrightarrow\ V_0 = G_7\ (G_3 + G_5 + G_4)\ V_1/\ \ G_3(G_7 + G_6) - G_5V_2/G_3 - G_5V_3/G_3$

Therefore $K_1 = G_7(G_3 + G_5 + G_4\ )/\ \ G_3\ \ (G_7 + G_6\ )$

$$K_2 = G_5\ /\ G_3\ ,\quad K_3 = G_4\ /\ G_3\ .$$

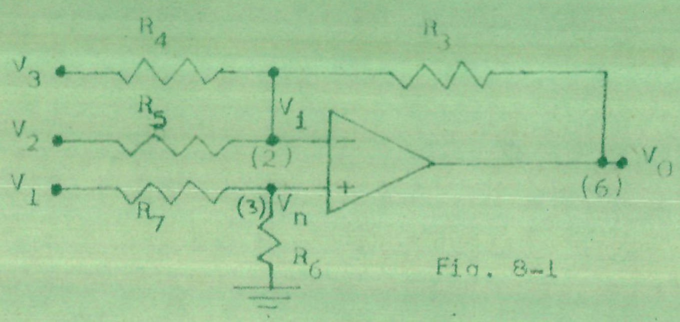
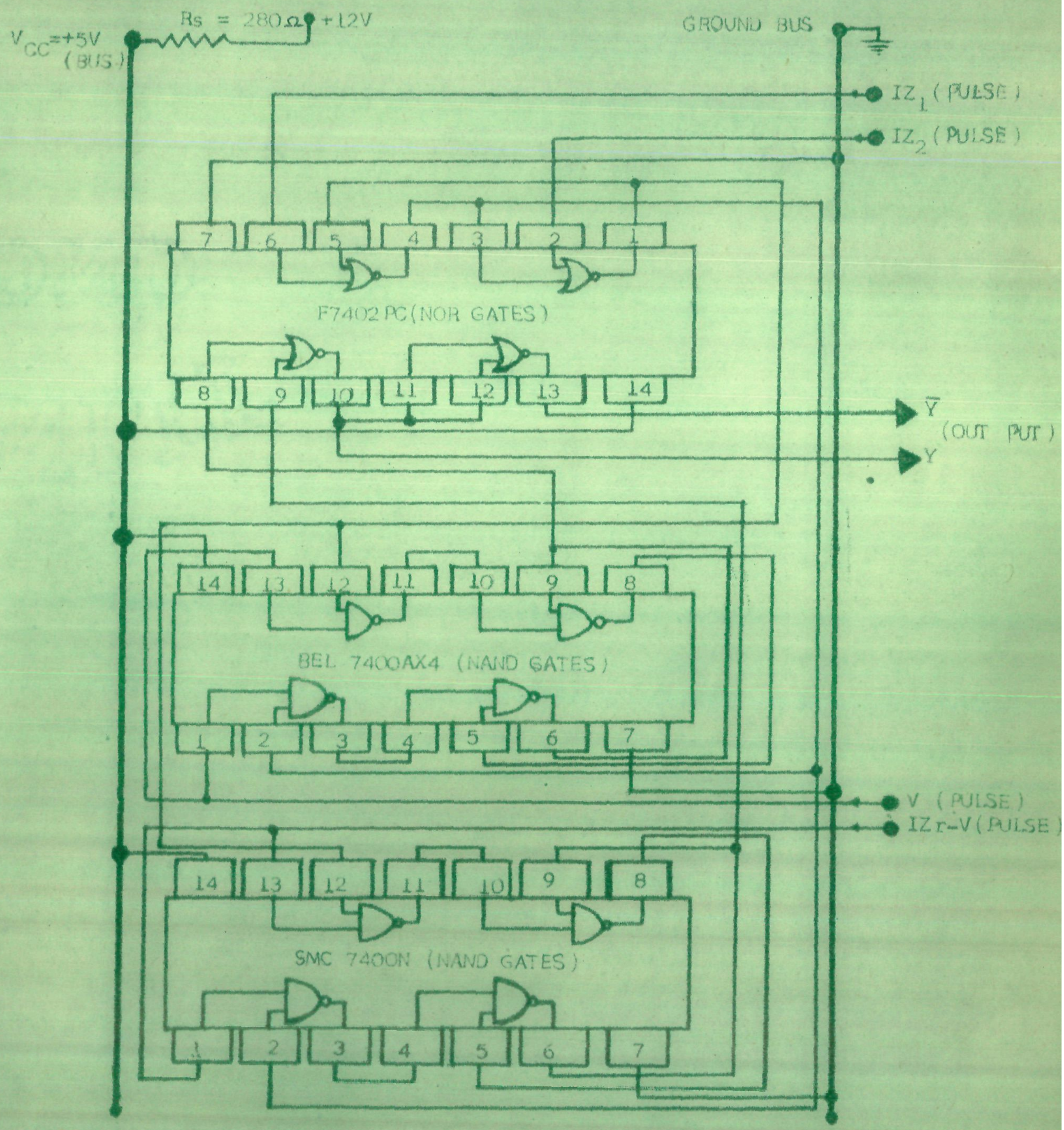
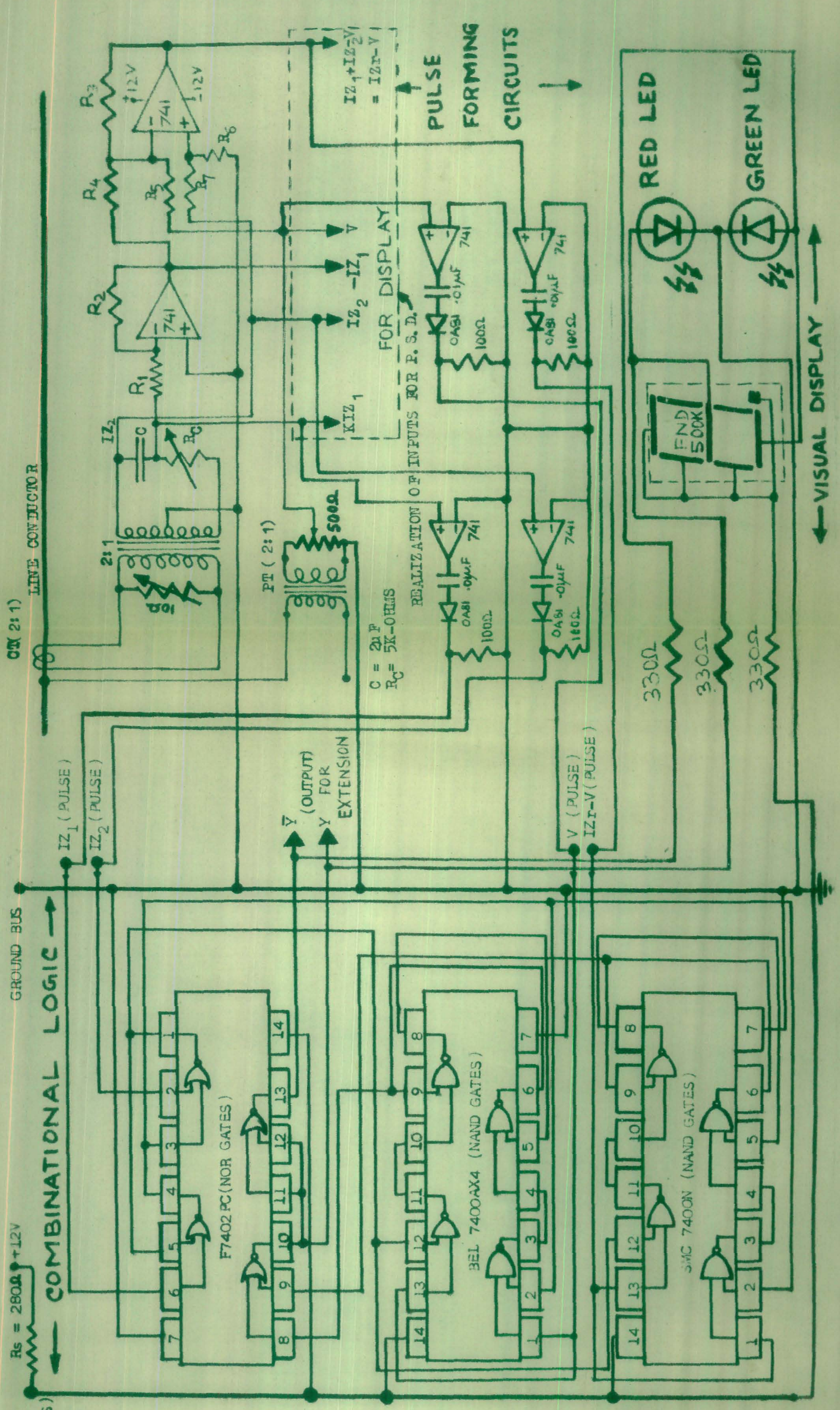
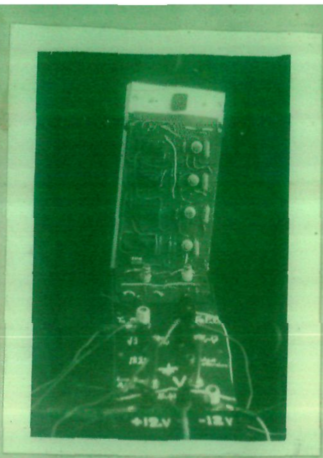

R4
R3
V3
R5
V1
V2
(2)
V0
V1
(6)
R7
(3) Vn
R6

Fig. 8-1

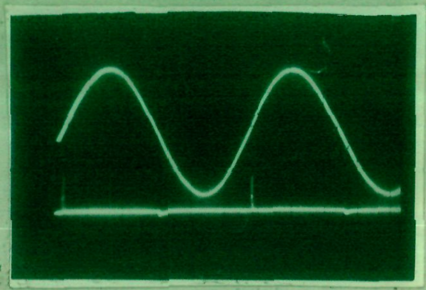

Rs = 280Ω
+12V
VCC=+5V
(BUS)
GROUND BUS
IZ1 (PULSE)
IZ2 (PULSE)
F7402 PC (NOR GATES)
Ȳ
(OUT PUT)
Y
BEL 7400AX4 (NAND GATES)
V (PULSE)
IZr-V (PULSE)
SMC 7400N (NAND GATES)



COMPLETE CIRCUIT DIAGRAM OF RELAY



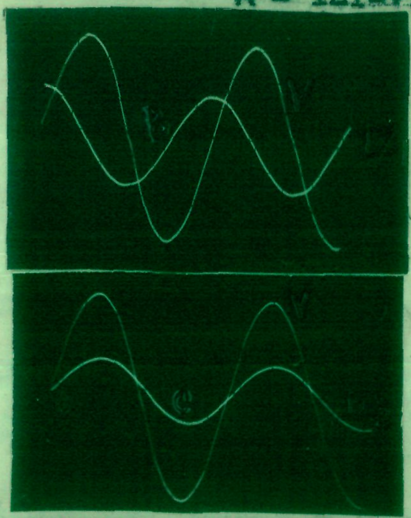
(THE DESIGNED RELAY)



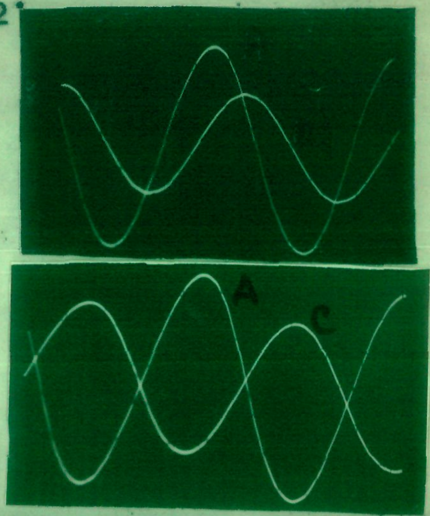
(SINOSOIDAL PHASOR AND ITS ZERO CROSS_OVER PULSES)

UNDER NORMAL LOADING CONDITION

$A = IZr-V$, $B = IZ_1$, $C = IZ_2$.

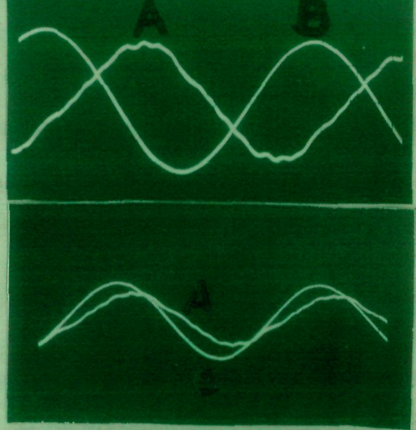


SEQUENCE - IZ_1, V, IZ_2



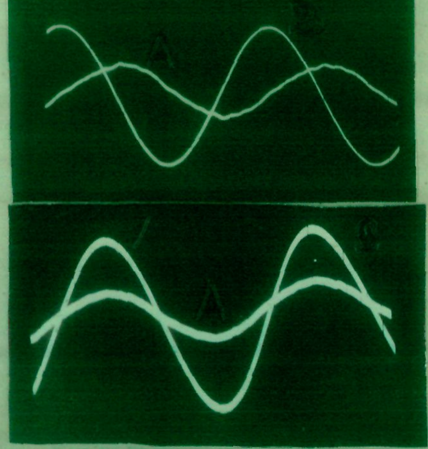
SEQUENCE - $IZr-V$, IZ_1, IZ_2.

FAULT OUTSIDE OF ZONE OF PROTECTION



SEQUENCE - IZ_1, IZ_2, $IZr-V$

FAULT INSIDE OF THE ZONE OF PROTECTION



SEQUENCE - IZ_1, $IZr-V$, IZ_2

Since $K_2 = K_3 = 1$; which gives, $G_5 = G_3 = G_4$

$$\text{or } R_5 = R_3 = R_4 \qquad \ldots\ldots (1)$$

Since $K_1 = 1$, $= 3G_3G_7 / G_3 (G_7+G_6) = 1$

Which gives $G_6 = 2G_7$ or $R_7 = 2R_6$ .... (2)

Therefore R_3, R_4, R_5, R_6 are taken 5.1 K-ohms and R_7 = 10.2 K-ohms.

Here $V_1 = IZ_2$, $V_2 = V$ and $V_3 = -IZ_1$.

Therefore $V_0 = IZ_2 - V + IZ_2 = I(Z_1 + Z_2) - V = IZr-V$.

The detailed connections of the designed P.S.D. is shown in the Fig. 8-2.

Photographs of the relay and the waveforms at different important instants are pasted.

R E F E R E N C E S

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